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REVIEW

Bioenergy and climate change mitigation: an assessment

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Abstract

Bioenergy deployment offers significant potential for climate change mitigation, but also carries considerable risks. In this review, we bring together perspectives of various communities involved in the research and regulation of bioenergy deployment in the context of climate change mitigation: Land-use and energy experts, land-use and integrated assessment modelers, human geographers, ecosystem researchers, climate scientists and two different strands of life-cycle assessment experts. We summarize technological options, outline the state-of-the-art knowledge on various climate effects, provide an update on estimates of technical resource potential and comprehensively identify sustainability effects. Cellulosic feedstocks, increased end-use efficiency, improved land carbon-stock management and residue use, and, when fully developed, BECCS appear as the most promising options, depending on development costs, implementation, learning, and risk management. Combined heat and power, efficient biomass cookstoves and small-scale power generation for rural areas can help to promote energy access and sustainable development, along with reduced emissions. We estimate the sustainable technical potential as up to 100 EJ: high agreement; 100–300 EJ: medium agreement; above 300 EJ: low agreement. Stabilization scenarios indicate that bioenergy may supply from 10 to 245 EJ yr^{-1} to global primary energy supply by 2050. Models indicate that, if technological and governance preconditions are met, large-scale deployment (>200 EJ), together with BECCS, could help to keep global warming below 2° degrees of preindustrial levels; but such high deployment of land-intensive bioenergy feedstocks could also lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods. The integration of bioenergy systems into agriculture and forest landscapes can improve land and water use efficiency and help address concerns about environmental impacts. We conclude that the high variability in pathways, uncertainties in technological development and ambiguity in political decision render forecasts on deployment levels and climate effects very difficult. However, uncertainty about projections should not preclude pursuing beneficial bioenergy options.

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Introduction

The recent IPCC report on energy sources and climate change mitigation (SRREN) and the Global Energy Assessment provided comprehensive overviews on bioenergy. An update to these reports is nonetheless important because: (i) many of the more stringent mitigation scenarios (resulting in 450 ppm, but also 550 ppm CO2eq concentration by 2100) heavily rely on a large-scale deployment of bioenergy with CO2 capture and storage (CCS) called BECCS technologies; (ii) there has been a large body of literature published since SRREN, which complement and update the analysis presented in this last report; (iii) bioenergy is important for many sectors and mitigation perspectives as well as from the perspective of developmental goals such as energy security and rural development.

The following text is based mostly, but not exclusively, on a draft of Chapter 11.13 of the Working Group 3 of the 5th Assessment Report of the IPCC (Smith *et al.*, 2014). This article itself represents exclusively the opinions of the authors and not those of the IPCC. It should also be noted that teams of authors worked on subsections and commented on other subsections. The result represents what we consider to be the state-of-the-art on assessing bioenergy, integrating a wide range of literature and perspectives. Given the contentious nature of the literature on bioenergy, it should not be surprising that the authors did not agree on all aspects of this review; thus we attempted to integrate the multiple perspectives present in the literature.

Bioenergy is energy derived from biomass, which can be deployed as solid, liquid and gaseous fuels for a wide range of uses, including transport, heating, electricity production, and cooking. Bioenergy systems can cause both positive and negative effects and their deployment needs to balance a range of environmental, social and economic objectives that are not always fully compatible. The consequences of bioenergy implementation depend on (i) the technology used; (ii) the location, scales and pace of implementation; (iii) the land category used (forest, grassland, marginal lands and crop lands); (iv) the governance systems; and (v) the business models and practices adopted, including how these integrate with or displace the existing land use.

We structure this article in six parts. In section How much bioenergy could be deployed in 2050, we first discuss the technical primary biomass potential for bioenergy. We then elaborate on the specific technological options available to make use of the biomass potential in section Bioenergy technologies. In section GHG emission estimates of bioenergy production systems, we summarize the literature assessing the attributional life-cycle emissions, and the (consequential) life-cycle land-use emissions. In section Future potential deployment in climate mitigation scenarios, we assess the overall role of bioenergy in stabilization scenarios. We then summarize the literature on bioenergy and sustainable development in section Bioenergy and sustainable development and consider trade-offs with other objectives in section Trade-offs and synergies with land, water, food and biodiversity. We conclude with a brief summary.

How much bioenergy could be deployed in 2050

The technical primary biomass potential for bioenergy – from here on referred to as 'technical bioenergy potential' – is the fraction of the theoretical potential (i.e., the theoretical maximum amount of biomass constrained only by biophysical limits) available with current technology. There is no standard methodology to estimate the technical bioenergy potential, which leads to diverging estimates. Most of the recent studies estimating technical bioenergy potentials assume a 'food/fiber first principle' and exclude deforestation, eventually resulting in an estimate of the 'environmentally sustainable bioenergy potential' when a comprehensive range of environmental constraints is considered (Batidzirai *et al.*, 2012).

Recently published estimates that are based in this extended definition of global technical primary biomass potentials in 2050 span a range of almost three orders of magnitude, from <50 EJ yr^{-1} to >1000 EJ yr^{-1} (Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Field *et al.*, 2008; Haberl *et al.*, 2010; Batidzirai *et al.*, 2012). For example, the SRREN reported global technical bioenergy potentials of 50–500 EJ yr^{-1} for the year 2050 (Chum *et al.*, 2011) and the Global Energy Assessment gave a range of 160–270 EJ yr^{-1} (Johansson *et al.*, 2012). The discussion following the publication of these global reports has not resulted in a consensus on the magnitude of the future global technical bioenergy potential, but has helped to better understand some of its many structural determinants (Berndes *et al.*, 2013; Erb *et al.*, 2012; Wirsenius *et al.*, 2010; Dornburg *et al.*, 2010).

Key point 1: How much biomass for energy is technically available in the future depends on the evolution of a multitude of social, political and economic factors, e.g., land tenure and regulation, diets, trade and technology.

Figure 1 shows estimates of the global technical bioenergy potential in 2050 by resource categories. Ranges were obtained from assessing a large number of studies based on a food/fiber first principle and various restrictions regarding resource limitations and environmental concerns but no explicit cost considerations (Chum *et al.*, 2011; Dornburg *et al.*, 2010; GEA, 2012 (Ch. 7,11,20); Gregg & Smith, 2010; Haberl *et al.*, 2010, 2011; Hakala *et al.*, 2009; Hoogwijk *et al.*, 2009, 2005; Rogner *et al.*, 2012; Smeets *et al.*, 2007; Smeets & Faaij, 2007; Van Vuuren *et al.*, 2009). Many studies agree that the technical bioenergy potential in 2050 is at least approximately 100 EJ yr^{-1} with some modeling assumptions leading to estimates exceeding 500 EJ yr^{-1} (Smeets *et al.*, 2007). As stated, different views about sustainability and socio-ecological constraints lead to very different estimates, with some studies reporting much lower figures.

As shown in Fig. 1, the total technical bioenergy potential is composed of several resource categories that differ in terms of their absolute potential, the span of the ranges –which also reflect the relative agreement/disagreement in the literature- and the implications of utilizing them. Regional differences – which are not addressed here – are also important as the relative size of each biomass resource within the total potential and its absolute magnitude vary widely across countries and world regions.

Forest and agriculture residues

Forest residues include residues from silvicultural thinning and logging; wood processing residues such as sawdust, bark and black liquor; dead wood from natural disturbances, such as storms and insect outbreaks (Smeets & Faaij, 2007; Smeets *et al.*, 2007; Dornburg *et al.*, 2010; Gregg & Smith, 2010; Haberl *et al.*, 2010; Rogner *et al.*, 2012). The use of these resources is in general beneficial. Adverse side effects can be mitigated by

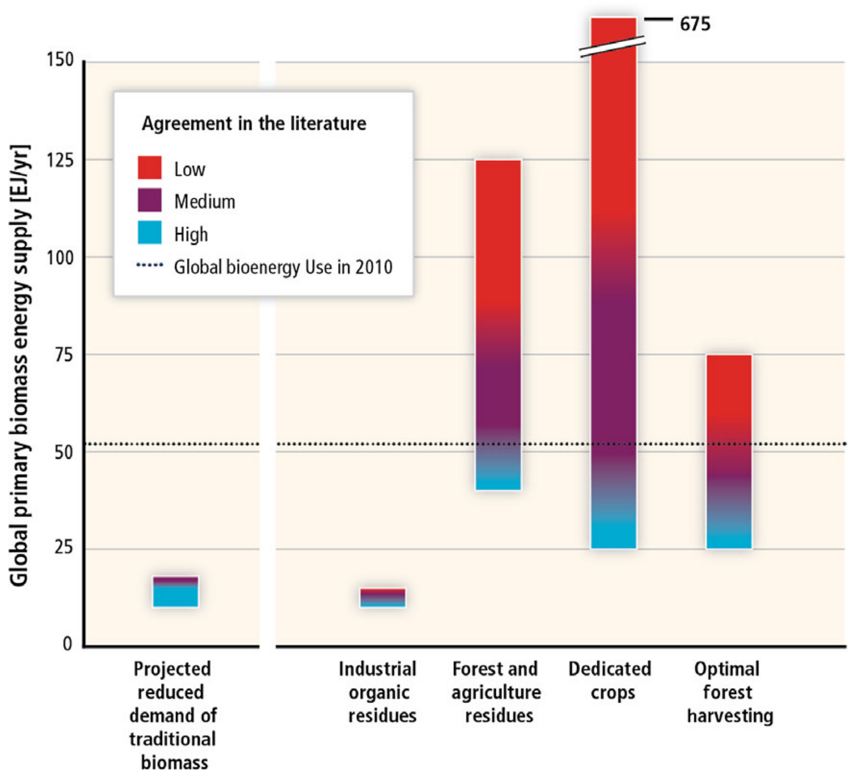


Fig. 1 Global Technical Primary Biomass Potential for Bioenergy by Main Resource Category for the year 2050. The Figure shows the ranges in the estimates by major resource category of the global technical primary biomass potential for bioenergy. The color grading is intended to show qualitatively the degree of agreement in the estimates, from blue (all researchers agree that this level can be attained) to purple (medium agreement) to red (few researchers agree that this level can be attained). In addition, reducing traditional biomass demand by increasing its use efficiency could release the saved biomass for other energy purposes with large benefits from a sustainable development perspective.

controlling residue removal rates considering biodiversity, climate, topography, and soil factors. There is a near term trade-off, particularly in temperate and boreal regions, in that organic matter retains organic C for longer if residues are left to decompose slowly instead of being used for energy (Repo *et al.*, 2012). Agricultural residues include manure, harvest residues (e.g., straw) and processing residues (e.g., rice husks from rice milling) and are also mostly beneficial (Smeets *et al.*, 2007; Hakala *et al.*, 2009; Gregg & Smith, 2010; Haberl *et al.*, 2010, 2011; Chum *et al.*, 2011; Rogner *et al.*, 2012). However, there may be adverse side effects – such as the loss of soil C and associated loss of fertility – associated to harvesting agriculture residues – which may affect the mitigation potential, but are difficult to assess on large scales as they depend on the specific combination of crops, climate and soil conditions (Kochsiek & Knops, 2012). Alternative uses of residues (bedding, use as fertilizer) need to be considered. Both agriculture and forestry residues have varying collection and processing costs, depending on residue quality and dispersal. Densification and storage technologies would enable cost-effective collections over larger areas.

Optimal forest harvesting is defined as the fraction of harvest levels (often set equal to net annual increment) in forests available for additional wood extraction if the projected harvest level resulting from the production of other forest products is taken into account. This includes both biomass suitable for other uses (e.g., pulp and paper production) and biomass that is not used commercially (Smeets & Faaij, 2007; Chum *et al.*, 2011). The resource potential depends on both environmental and socio-economic factors. For example, the change in forest management and harvesting regimes due to bioenergy demand depends on forest ownership, economic incentives and the structure of the associated forest industry. Also, the forest productivity and C-stock-response to changes in forest management and harvesting depend on the character of the forest ecosystem, as shaped by historic forest management and events such as fires, storms and insect outbreaks, but also on the management scheme, e.g., including replanting after harvest, soil protection, recycling of nutrients and soil types (Berndes *et al.*, 2013; Jonker *et al.*, 2013; Lamers *et al.*, 2013). In particular, optimizing forest management for mitigation is a complex issue with many uncertainties and still subject to scientific debate (see section GHG emission estimates of bioenergy production systems).

Organic wastes include waste from households and restaurants, discarded wood products such as paper, construction, and demolition wood waste, and waste waters suitable for anaerobic biogas production (Gregg & Smith, 2010; Haberl *et al.*, 2010). Organic waste may be dispersed and heterogeneous in quality but the health and environmental gains from collection and proper management through combustion or anaerobic digestion can be significant. Competition with alternative uses of the wastes may limit this resource potential.

Dedicated biomass plantations include annual (cereals, oil- and sugar crops) and perennial plants (e.g., switchgrass, Miscanthus) and tree plantations including both coppice and single-stem plantations (e.g., willow, poplar, eucalyptus, pine) (Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Van Vuuren *et al.*, 2009; Dornburg *et al.*, 2010; Wicke *et al.*, 2011a). The range of estimates of technical bioenergy potentials from that resource in 2050 is particularly large (<50 to >500 EJ yr^{-1}). Technical bioenergy potentials from dedicated biomass plantations are generally calculated by multiplying (i) the area deemed available for energy crops by (ii) the yield per unit area and year (Batidzirai *et al.*, 2012; Coelho *et al.*, 2012). Some studies have identified a sizable technical potential (up to 100 EJ yr^{-1}) for bioenergy production using marginal and degraded lands (e.g., saline land) that are currently not in use for crop production or grazing (Nijsen *et al.*, 2012). However, how much land is really unused and available is contested (Erb *et al.*, 2007; Haberl *et al.*, 2010, 2011; Coelho *et al.*, 2012; Dauber *et al.*, 2012). Contrasting views on future technical bioenergy potentials from dedicated biomass plantations can be explained by differences in assumptions regarding feasible future agricultural crop yields, diet shifts, livestock feeding efficiency, land availability for energy crops and yields of energy crops (Dornburg *et al.*, 2010; Batidzirai *et al.*, 2012; Erb *et al.*, 2012). Many scientists agree that increases in food crop yields and higher feeding efficiencies and lower consumption of animal products would result in higher technical bioenergy potential.

Reduced traditional biomass demand

A substantial quantity of biomass will become available for modern applications by improving the end-use efficiency of traditional biomass consumption for energy, mostly in households but also within small industries (such as charcoal kilns, brick kilns, etc.). Traditional bioenergy represents approximately 15% of total global energy use and 80% of current bioenergy use ($\approx$35 EJ yr^{-1}) and helps meeting the cooking and heating needs of ~2.7 billion people (Chum *et al.*, 2011). Cooking is the dominant end use; it is mostly done in open fires and rudimentary stoves, with approximately 10–20% conversion efficiency, leading to very high primary energy consumption. Advanced woodburning and biogas stoves can potentially reduce biomass fuel consumption by 60% or more (Jetter *et al.*, 2012) and further reduce CO_2 emissions, and in many cases black carbon emissions, by up to 90% (Anenberg *et al.*, 2013). Assuming that actual savings reach on average from 30% to 60% of current consumption, the total bioenergy potential from reducing traditional bioenergy demand can be estimated at 8–18 EJ yr^{-1}. An unknown fraction of global traditional biomass is consumed in a nonenvironmentally sustainable way, leading to forest degradation and deforestation. Detailed country studies have estimated the fraction of nonrenewable biomass from traditional bioenergy use to vary widely – e.g., from 1.6% for the Democratic Republic of Congo to 73% for Burundi (UNFCCC-CDM, 2012) – with most countries in the range between 10–30% (i.e., meaning that 70–90% of total traditional bioenergy use is managed sustainably). If that biomass could be saved through better technology, this would help restoring local ecosystems" (HH).

Bioenergy technologies

Conversion technologies

Numerous conversion technologies can transform biomass to heat, power, liquid and gaseous fuels for use in the residential, industrial, transport and power sectors (Chum *et al.*, 2011 and GEA, 2012; Edenhofer *et al.*, 2013; Fig. 2 for the pathways concerning liquid and gaseous fuels). Since SRREN, the major advances in the large-scale production of bioenergy include the increasing use of hybrid biomass-fossil fuel systems. For example, the use of current commercial coal and biomass cocombustion technologies belong to the lowest cost technologies to implement renewable energy policies, enabled by the large-scale pelletized feedstocks trade (REN21, 2013; Junginger *et al.*, 2014). Using biomass for combined power and heat, either cofired with coal or not, coupled to a network of district heating (to avoid cooling energy losses) and biochemical processing of waste biomass, are among the most cost-efficient and effective biomass applications for GHG emission reduction (Sterner & Fritsche, 2011).

Integrated gasification combined cycle (IGCC) technologies for coproduction of electricity and liquid fuels from coal and biomass with higher efficiency than current commercial processes are in demonstration phase to reduce cost (GEA, 2012; Larson *et al.*, 2012). Coupling of biomass and natural gas for fuels is another option for liquid fuels (Baliban *et al.*, 2013) as the biomass gasification technology development progresses. Simulations suggest that integrated gasification facilities are technically feasible (with up to 50% biomass input) (Meerman *et al.*, 2011) and economically attractive with a CO_2 price of about 50€/tCO_2 (Meerman *et al.*, 2012).

Many pathways and feedstocks can lead to biofuels for aviation (Fig. 2). The development of biofuel standards enabled domestic and transatlantic flights testing of 50% biofuel in jet fuel (REN21, 2012, 2013). Advanced 'drop in' fuels, such as iso-butanol, synthetic aviation kerosene from biomass gasification or upgrading of pyrolysis liquids, can be derived through a number of

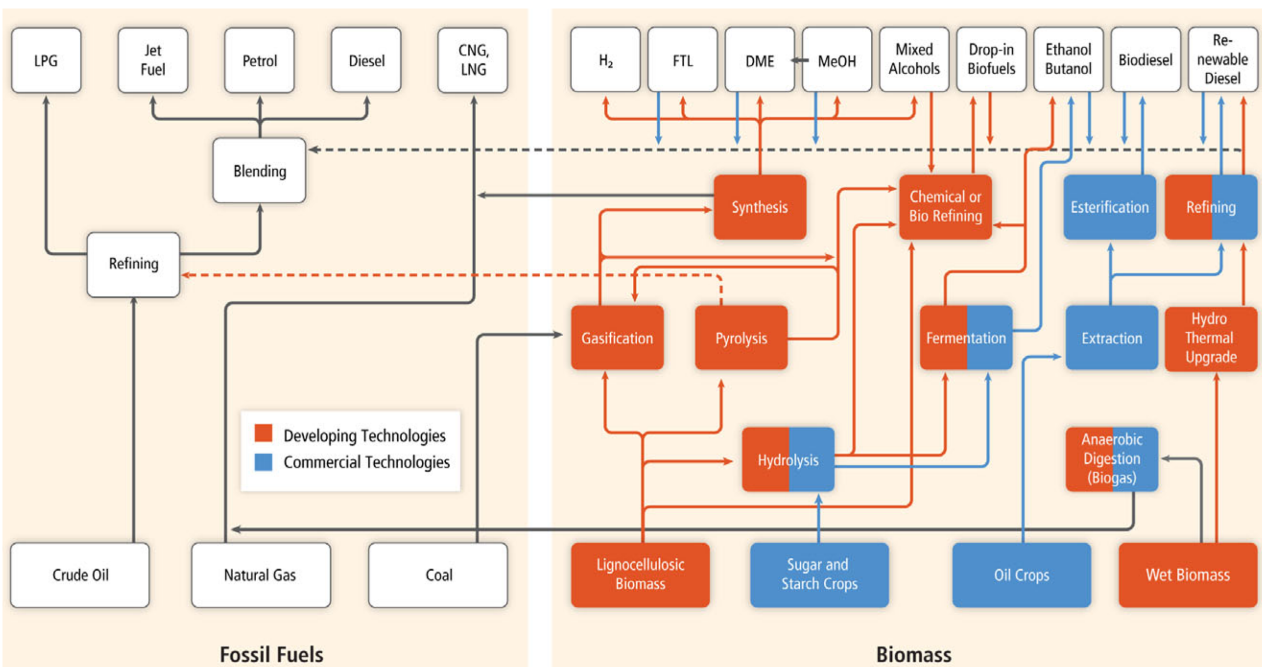


Fig. 2 Production pathways to liquid and gaseous fuels from biomass and, for comparison from fossil fuels (adapted from Turkenburg *et al.*, 2012; GEA, 2012, Chapter 11).

possible conversion routes such as hydro treatment of vegetable oils, iso-butanol, and Fischer-Tropsch synthesis from gasification of biomass (Hamelinck & Faaij, 2006; Bacovsky *et al.*, 2010; Meerman *et al.*, 2011, 2012; Rosillo-Calle *et al.*, 2012). In most cases, powering electric cars with electricity from biomass has higher land-use efficiency and lower GWP effects than the usage of bioethanol from biofuel crops for road transport across a range of feedstocks, conversion technologies, and vehicle classes (Campbell *et al.*, 2009; Schmidt *et al.*, 2011), though costs remain a barrier (Schmidt *et al.*, 2011; Van Vliet *et al.*, 2011a,b).

The number of routes from biomass to a broad range of biofuels, shown in Fig. 2, includes hydrocarbons connecting today's fossil fuels industry in familiar thermal/catalytic routes such as gasification (Larson *et al.*, 2012) and pyrolysis (Bridgwater, 2012; Elliott, 2013; Meier *et al.*, 2013). In addition, advances in genomic technology and the integration between engineering, physics, chemistry, and biology points to new approaches in biomass conversion (Liao & Messing, 2012), such as biomolecular engineering (Li *et al.*, 2010; Peralta-Yahya *et al.*, 2012; Favaro *et al.*, 2013; Lee *et al.*, 2013; Yoon *et al.*, 2013). Advances in (bio)-catalysis and basic understanding of the synthesis of cellulose indicate alternative conversion pathways for fuels and chemicals under mild conditions (Serrano-Ruiz *et al.*, 2010; Carpita, 2012; Shen *et al.*, 2013; Triantafyllidis *et al.*, 2013; Yoon *et al.*, 2013).

Beccs

Bioenergy coupled with CO_2 Capture and Storage (BECCS) (Spath & Mann, 2004; Liu *et al.*, 2010, 2011) can mitigate climate change through negative emissions if CCS can be successfully deployed (Lenton & Vaughan, 2009; Cao & Caldeira, 2010). BECCS features prominently in long-run mitigation scenarios for two reasons: (i) The potential for negative emissions may allow shifting emissions in time; and (ii) Negative emissions from BECCS can compensate for residual emissions in other sectors (most importantly transport) in the second half of the 21st century. As illustrated in Fig. 3, BECCS is markedly different than fossil CCS because it not only reduces CO_2 emissions by storing C in long term geological sinks, but it continually sequesters CO_2 from the air through regeneration of the biomass resource feedstock (depending on the accounting framework, see section GHG emission estimates of bioenergy production systems).

BECCS deployment is in the development and exploration stages. The most relevant BECCS project is the Illinois Basin – Decatur Project (IBDP) that is projected to store 1 Mt CO_2 yr^{-1} (Gollakota & McDonald, 2012; Senel & Chugunov, 2013). In the US, two ethanol fuel production facilities are currently integrated commercially with carbon dioxide capture, pipeline transport, and use in enhanced oil recovery in nearby facilities at a rate of about 0.2 Mt CO_2 yr^{-1} (DiPietro *et al.*, 2012). Altogether there are 16 global BECCS projects in the exploration stage (Karlsson & Byström, 2011).

Critical to overall CO_2 storage is the realization of a lignocellulosic biomass supply infrastructure for large-scale commodity feedstock production and efficient advanced conversion technologies at scale; both benefit from cost reductions and technological learning as does the integrated system with CCS, with financial and institutional conditions that minimize the risks of investment and facilitate dissemination (Eranki & Dale, 2011; IEA, 2012, 2013). Integrated analysis is needed to capture system and knock-on effects for bioenergy potentials (IEA, 2013). A nascent feedstock infrastructure for densified biomass trading globally could indicate decreased pressure on the need for closely colocated storage and production (IEA, 2011; Junginger *et al.*, 2014). However, bioenergy products commonly have lower energy density than their fossil alternatives and supply chains may be associated with higher GHG emissions.

Koornneef *et al.* (2012, 2013) estimate the overall technical potential to be around 10Gt CO_2 storage per year for both IGCC-CCS cofiring (i.e., Integrated Gasification Combined Cycle with cogasification of biomass), and BIGCC-CCS (Biomass Integrated Gasification Combined Cycle), and around 6 Gt CO_2 storage for FT diesel (i.e., Biodiesel based on gasification and Fischer–Tropsch synthesis), and 2.7 Gt CO_2 for biomethane production. McLaren (2012) estimates the potential capacity (similar to technical potential) to be between 2.4 and 10 Gt CO2 per year for 2030–2050. The economic potential, at a CO_2 price of around 70$/tCO2 is estimated to be around 3.3 Gt CO2, 3.5 Gt CO2, 3.1 Gt CO2 and 0.8 Gt CO2 in the corresponding four cases, judged to be those with highest economic potential (Koornneef *et al.*, 2012, 2013).Potentials are assessed on a route-by-route basis and cannot simply be added, as they may compete and substitute each other. Practical figures might be not much higher than 2.4 Gt CO_2 per year at 70–250\$/tCO_2 (McLaren, 2012). Altogether, until 2050 the economic potential is anywhere between 2 and 10 Gt CO_2 per year. Some climate stabilization scenarios project considerable higher deployment toward the end of the century, even in some 580–650 ppm scenarios, operating under different time scales, socio-economic assumptions, technology portfolios, CO_2 prices, and interpreting BECCS as part of an overall mitigation framework (e.g., Rose *et al.*, 2012; Kriegler *et al.*, 2013; Tavoni & Socolow, 2013).

Key point 2: The economic potential of BECCS is uncertain but could lie in the range of 2–10 Gt CO_2 per year in 2050.

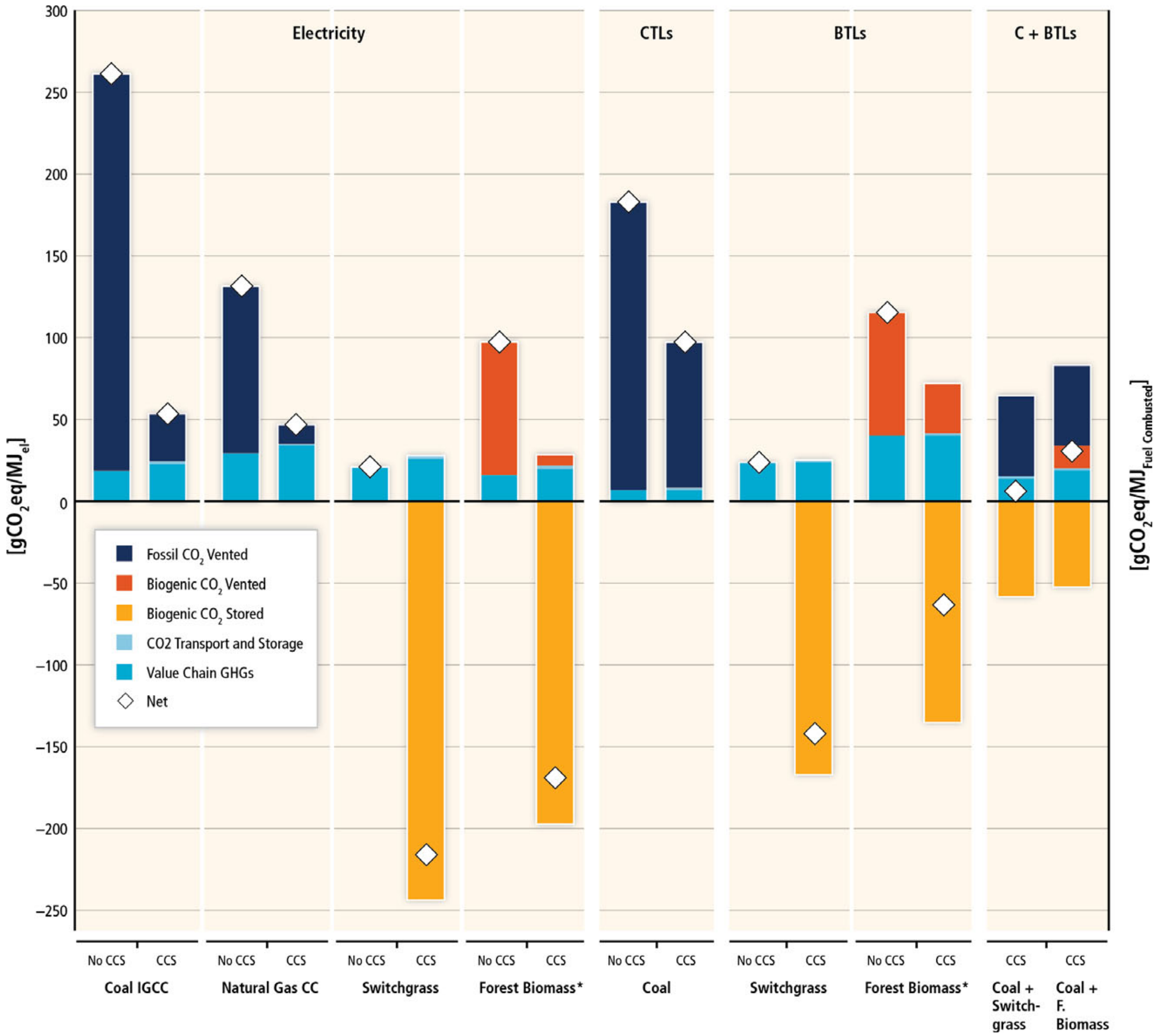


Fig. 3 Illustration of the sum of CO_2-equivalent (GWP_{100}: Global Warming Potential over 100 years) emissions from the process chain of alternative transport and power generation technologies both with and without CCS. Values are uncertain and depend on the production chain as well as what and how biomass is sourced. Differences in C-density between forest biomass and switchgrass are taken into account but not calorific values (balance-of-plant data are for switchgrass, Larson *et al*., 2012). Estimated emissions vary with biomass feedstock and conversion technology combinations, as well as life-cycle GHG calculation boundaries. For policy relevant purposes, counterfactual and market-mediated aspects (e.g., indirect land use change: ILUC), changes in soil organic carbon, or changes in surface albedo need also to be considered, possibly leading to significantly different outcomes (Section GHG emission estimates of bioenergy production systems, Figs 4 and 5). Units: g-CO_2-eq. MJ_{El} (left *y*-axis, electricity); g-CO_2-eq. MJ^{-1} combusted (right *y*-axis, transport fuels). Direct CO_2 emissions from energy conversion ('vented' and 'stored') are adapted from the mean values in Tables 12.7, 12.8, and 12.15 of reference (1), which are based on the work of references (2, 3), and characterized with the emission metrics in reference (4). Impacts upstream in the supply chain associated with feedstock procurement (i.e., sum of GHGs from mining/cultivation, transport, etc.) are adapted from references (5, 6) and Fig. 4 (mean values). (1) Larson *et al*., 2012; (2) Woods *et al*., 2007; (3) Liu *et al*., 2010; (4) Guest *et al*., 2013; (5) Turconi *et al*., 2013; (6) Jaramillo *et al*., 2008).

Possible climate risks of BECCS relate to reduction of land carbon stock, feasible scales of biomass production and increased N_2O emissions, and potential leakage of CO_2 stored in deep geologic reservoirs (Rhodes & Keith, 2008). The assumptions of sufficient spatially appropriate CCS capture, pipeline and storage infrastructure are uncertain. The literature highlights that BECCS as well as CCS deployment is dependent on strong financial incentives, as they are not cost competitive otherwise.

Figure 3 illustrates some GHG effects associated with BECCS pathways. Trade-offs between CO_2 capture rate and feedstock conversion efficiency are possible. Depending on the feedstock, technology, and energy product, energy penalties with CCS span ~10–20% (Liu *et al.*, 2011; Larson *et al.*, 2012). Depicted are pathways with the highest removal rate but not necessarily with the highest feedstock conversion rate. Among all BECCS pathways, those based on integrated gasification combined cycle produce most significant geologic storage potential from biomass, alone (shown in Fig. 4, electricity) or coupled with coal. Fischer-Tropsch diesel fuel production with biomass as feedstock and CCS attached to plant facilities could enable BECCS for transport; uncertainties in input factors and output metrics warrant further research (Van Vliet *et al.*, 2009); Fischer-Tropsch diesel would also allow net removal but at lower rates than BIGCC.

Microalgea and cellulosic biofuels

Microalgae offer an alternative to land-based bioenergy. Its high-end technical potential might be compromised by water supply, if produced in arid land, or by its

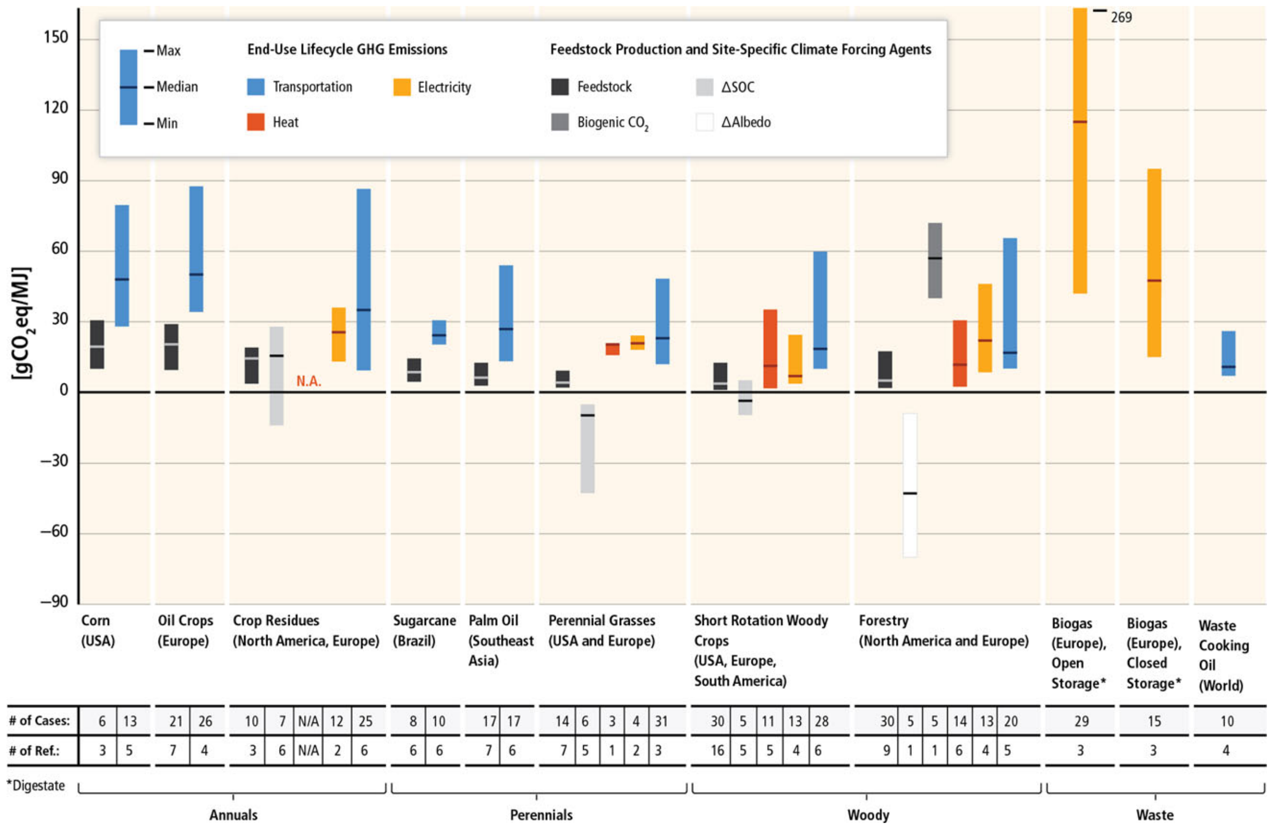


Fig. 4 The sum of CO_2-equivalent (GWP100) emissions from the process chain of major bioenergy product systems, not including emissions from market-mediated effects such as land-use change (see Fig. 5). The interpretation of values depends also on baseline assumption about the land carbon sink when appropriate and the intertemporal accounting frame chosen, and should also consider information from Fig. 5. The lower and upper bounds of the bars represent the minimum and the maximum value reported in the literature. Whenever possible, only peer-reviewed scientific literature published post SRREN is used (but results are comparable). Note that narrow ranges may be an artifact of the number of studies for a given case. Results are disaggregated in a manner showing the impact of *Feedstock* production (in g CO_2-eq. MJ^{-1} LHV of feedstock) and the contributions from end product/conversion technology. Results from conversion into final energy products *Heat*, *Power*, and *Transport fuels* include the contribution from *Feedstock* production and are shown in g CO_2-eq. MJ^{-1} of final product. For some pathways, additional site-specific climate forcing agents apply and are presented as separate values to be added or subtracted from the value indicated by the mean in the *Feedstock* bar (green). Final products are also affected by these factors, but this is not displayed here. References are provided in Table S1. Note that the biofuels technologies for transport from lignocellulosic feedstocks, short rotation woody crops, and crop residues, including collection and delivery, are developing so larger ranges are expected than for more mature commercial technologies such as sugarcane ethanol and WCO biodiesel. The biogas electricity bar represents scenarios using LCAs to explore treating mixtures of a variety of lignocellulosic feedstocks (e.g., ensiled grain or agricultural residues or perennial grasses) with more easily biodegradable wastes (e.g., from animal husbandry), to optimize multiple outputs. Variations in CH_4 leakage of biogas systems leads to a broad range of life-cycle emissions.

impact on ocean ecosystems. To make algae cost competitive, maximizing algal lipid content (and then maximizing growth rate) require essential technological breakthroughs (Davis *et al.*, 2011; Sun *et al.*, 2011; Jonker & Faaij, 2013). Its market potential depends on the co-use of products for food, fodder, higher value products, and on fuel markets (Chum *et al.*, 2011).

Similarly, lignocellulosic feedstocks produced from waste or residues, or grown on land unsupportive of food production (e.g., contaminated land for remediation as in previously mined land) have been suggested to reduce socio-environmental impact. In addition, lignocellulosic feedstocks can be bred specifically for energy purposes, and can be harvested by coupling collection and preprocessing (densification and others) in depots prior to final conversion, which could enable delivery of more uniform feedstocks throughout the year (Eranki & Dale, 2011; US DOE, 2011; Argo *et al.*, 2013). Various conversion pathways are in R&D, near commercialization, or in early deployment stages in several countries (see 2.6.3 in Chum *et al.*, 2011). Crops suitable for cultivation on marginal land can compete with food crops unless land prices rise to make cultivation on marginal land preferable, i.e., land-use competition can still arise. Depending on the feedstock, conversion process, prior land use, and land demand, lignocellulosic bioenergy can be associated with high or low GHG emissions (e.g., Davis *et al.*, 2012).

Cookstoves

Substantial progress has also been achieved in the last 4 years in small-scale bioenergy applications in the areas of technology innovation, impact evaluation and monitoring and in large-scale implementation programs. Advanced combustion biomass cookstoves reduce fuel use by more than 60% and hazardous pollutant as well as short-lived climate pollutants by up to 90% (Kar *et al.*, 2012; Anenberg *et al.*, 2013). Innovative designs include micro-gasifiers, stoves with thermoelectric generators to improve combustion efficiency and provide electricity to charge LED lamps while cooking, stoves with advanced combustion chamber designs and multi-use stoves (e.g., cooking and water heating for bathing) (Ürge-Vorsatz *et al.*, 2012; Anenberg *et al.*, 2013). Biogas stoves, in addition to providing clean combustion, help reduce the health risks associated to the disposal of organic wastes. There has also been a boost in cookstove dissemination efforts ranging from regional (multicountry) initiatives (Wang *et al.*, 2013) to national, and project level interventions. In total more than 200 cookstove large-scale projects are in place worldwide, with several million efficient cookstoves installed each year (Cordes, 2011). A Global Alliance for Clean Cook stoves has been launched that is promoting the adoption of 100 million clean and efficient cookstoves per year by 2030 and several countries have launched National Cookstove Programs in recent years (e.g., Mexico, Peru, Honduras, and others). Many cookstove models are now manufactured in large-scale industrial facilities using state-of-the-art materials and combustion design technology. Significant efforts are also in place to develop international standards and regional stove testing facilities. In addition to providing tangible local health and other sustainable benefits, replacing traditional open fires with efficient biomass cookstoves has a global mitigation potential estimated in between 0.6 and 2.4 Gt CO_2-eq yr^{-1} (Ürge-Vorsatz *et al.*, 2012). Small-scale decentralized biomass power generation systems based on biomass combustion and gasification and biogas production systems have the potential to meet the electricity needs of rural communities in the developing and developed countries alike. The biomass feedstocks for these small-scale systems could come from residues of crops and forests, wastes from livestock production and/or from small-scale energy plantations (Faaij, 2006).

Key point 3: Advanced combustion biomass cookstoves reduce fuel use by more than 60% and hazardous pollutant as well as short-lived climate pollutants by up to 90%.

GHG emission estimates of bioenergy production systems

The combustion of biomass generates gross GHG emissions roughly equivalent to those from combustion of fossil fuels. If bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils. The appropriate comparison is then between the net biosphere flux in the absence of bioenergy compared to the net biosphere flux in the presence of bioenergy production. Direct and indirect effects need to be considered in calculating these fluxes.

Bioenergy systems directly influence local and global climate through: (i) GHG emissions from fossil fuels associated with biomass production, harvest, transport, and conversion to secondary energy carriers (Von Blottnitz & Curran, 2007; Van der Voet *et al.*, 2010); (ii) CO_2 and other GHG emissions from biomass or biofuel combustion (Cherubini *et al.* 2011); (iii) atmosphere-ecosystem exchanges of CO_2 following land disturbance (Berndes *et al.*, 2013; Haberl, 2013); (iv) non-CO_2 GHG emissions of short-lived GHGs like black carbon and other chemically active gases (NO_x, CO, etc.) (Jetter *et al.*, 2012; Tsao *et al.*, 2012) and non-CO_2 GHGs from land management and perturbations to soil biogeochemistry, e.g., N_2O from fertilizers, and CH_4 (Cai *et al*., 2001); (v) climate forcing resulting from alteration of biophysical properties of the land surface affecting the surface energy balance (e.g., from changes in surface albedo, heat and water fluxes, surface roughness, etc.) (Bonan, 2008; West *et al*., 2010; Pielke *et al*., 2011). Market-mediated 'indirect' effects include the partial or complete substitution of fossil fuels and the indirect transformation of land use by equilibrium effects. Hence, the total climate forcing of bioenergy depends on feedstock, site-specific climate and ecosystems, management conditions, production pathway, end use, and on the interdependencies with energy and land markets.

Bioenergy systems have often been assessed (e.g., in LCA studies, integrated assessment models, policy directives) under the assumption that the CO_2 emitted from biomass combustion is climate neutral because the carbon that was previously sequestered from the atmosphere is returned to the atmosphere in combustion if the bioenergy system is managed sustainably (Chum *et al*., 2011; Creutzig *et al*., 2012a,b). The neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories, e.g., IPCC – Land Use, Land-Use Change and Forestry (2000) states 'Biomass fuels are included in the national energy and carbon dioxide emissions accounts for informational purposes only. Within the energy module biomass consumption is assumed to equal its regrowth. Any departures from this hypothesis are counted within the Land Use Change and Forestry Model.' Carbon neutrality is valid if the countries account for LUC in their inventories for self-produced bioenergy. The shortcomings of this assumption have been extensively discussed (Haberl, 2013; Searchinger, 2010; Searchinger *et al*., 2009; Cherubini *et al.* 2011).

Studies also call for a consistent and case-specific carbon-stock/flux change accounting that integrates the biomass system with the global carbon cycle (Mackey *et al*., 2013). As shown in the Working Group I of the AR5 (Myhre & Shindell, 2013) and elsewhere (Plattner *et al*., 2009; Fuglestvedt *et al*., 2010), the climate impacts can be quantified at different points along a cause-effect chain, from emissions to changes in temperature and sea level rise. While a simple sum of the net CO_2 fluxes over time can inform about the skewed time distribution between sources and sinks ('C debt') (Marland & Schlamadinger, 1995; Fargione *et al*., 2008; Bernier & Paré, 2013), understanding the climate implications as it relates to policy targets (e.g., limiting warming to 2 °C) requires models and/or metrics that also include temperature effects and climate consequences (Tanaka *et al*., 2013). While the warming from fossil fuels is nearly permanent as it persists for thousands of years, direct impacts from renewable bioenergy systems cause a perturbation in global temperature that is temporary and even at times leads to cooling if terrestrial carbon stocks are not depleted (House *et al*., 2002; Cherubini *et al*., 2013; Joos *et al*., 2013; Mackey *et al*., 2013). For example, in the specific case of existing forests that may continue to grow if not used for bioenergy, some studies employing counterfactual baselines show that forest bioenergy systems can have higher cumulative CO_2 emissions than a fossil reference system (for a time period ranging from few decades up to several centuries) (Pingoud *et al*., 2012; Bernier & Paré, 2013; Guest *et al*., 2013; Holtsmark, 2013). In some cases, cooling contributions from changes in surface albedo can mitigate or offset these effects (Anderson-Teixeira *et al*., 2012; Arora & Montenegro, 2011; O'Halloran *et al*., 2012; Hallgren *et al*., 2013).

Accounting always depends on the spatial and temporal system boundaries adopted when assessing climate change impacts, and the assumed baseline, and hence includes value judgements (Schwietzke *et al*., 2011; Cherubini *et al*., 2013; Kløverpris & Mueller, 2013).

Two specific contributions to the climate forcing of bioenergy, not addressed in detail in SRREN include nitrous oxide and biogeophysical factors.

Nitrous oxide (N_2O) emissions

for first-generation crop-based biofuels, as with food crops, emissions of N_2O from agricultural soils is the single largest contributor to direct GHG emissions, and one of the largest contributors across many biofuel production cycles (Smeets *et al*., 2009; Hsu *et al*., 2010). Emission rates can vary by as much as 700% between different crop types for the same site, fertilization rate and measurement period (Kaiser & Ruser, 2000; Don *et al*., 2012; Yang *et al*., 2012). In some locations, N_2O emissions can so high that some biofuel systems that are expected to deliver significant GHG savings can cause higher GHG emissions than the fossil fuels displaced (Smith *et al*., 2012b). Improvements in nitrogen use efficiency and nitrogen inhibitors can substantially reduce emissions of N_2O (Robertson & Vitousek, 2009). For some specific crops, such as sugarcane, N_2O emissions can be low (Macedo *et al*., 2008; Seabra *et al*., 2011) or high (Lisboa *et al*., 2011). Some bioenergy crops require relatively limited N input and can reduce GHG emissions relative to the former land use where they replace conventional food crops (Clair *et al*., 2008).

Biogeophysical factors

Land cover changes or land-use disturbances of the surface energy balance, such as surface albedo, surface roughness, and evapotranspiration influence the climate system (Betts, 2001, 2007; Marland *et al.*, 2003; Bonan, 2008; Jackson *et al.*, 2008). Perturbations to these can lead to both direct and indirect climate forcings whose impacts can differ in spatial extent (global and/or local) (Bala *et al.*, 2007; Davin *et al.*, 2007). Surface albedo is found to be the dominant direct biogeophysical climate impact mechanism linked to land cover change at the global scale, especially in areas with seasonal snow cover (Claussen *et al.*, 2001; Bathiany *et al.*, 2010), with radiative forcing effects possibly stronger than those of the cooccuring C-cycle changes (Randerson *et al.*, 2006; Lohila *et al.*, 2010; Bright *et al.*, 2011; O'Halloran *et al.*, 2012). Land cover changes can also affect other biogeophysical factors like evapotranspiration and surface roughness, which can have important local (Georgescu *et al.*, 2011; Loarie *et al.*, 2011) and global climatic consequences (Bala *et al.*, 2007; Swann *et al.*, 2010, 2011). Biogeophysical climate impacts from changes in land use are site specific and show variations in magnitude across different geographic regions and biomes (Bonan, 2008; Jackson *et al.*, 2008; Anderson *et al.*, 2011; Betts, 2011; Arora & Montenegro, 2011; Anderson-Teixeira *et al.*, 2012; Pielke *et al.*, 2011).

Key point 4: Assessing land-use mitigation options should include evaluating biogeophysical impacts, such as albedo modifications, as their size may be comparable to impacts from changes to the C cycle.

Attributional life-cycle impacts

Figure 4 illustrates the range of life-cycle global direct climate impact (in g CO_2 equivalents per MJ, after characterization with GWP time horizon = 100 years) attributed to major global bioenergy products reported in the peer-reviewed literature after 2010. Results are broadly comparable to those of Chapter 2 in SRREN (Figure 2.10 and 2.11 in SRREN; those figures displayed negative emissions, resulting from crediting emission reduction due to substitution effects; this article does not allocate credits to feedstocks to avoid double accounting). Significant variation in the results reflects the wide range of conversion technologies and their reported performances in addition to analyst assumptions affecting system boundary completeness, emission inventory completeness, and choice of allocation method (among others).

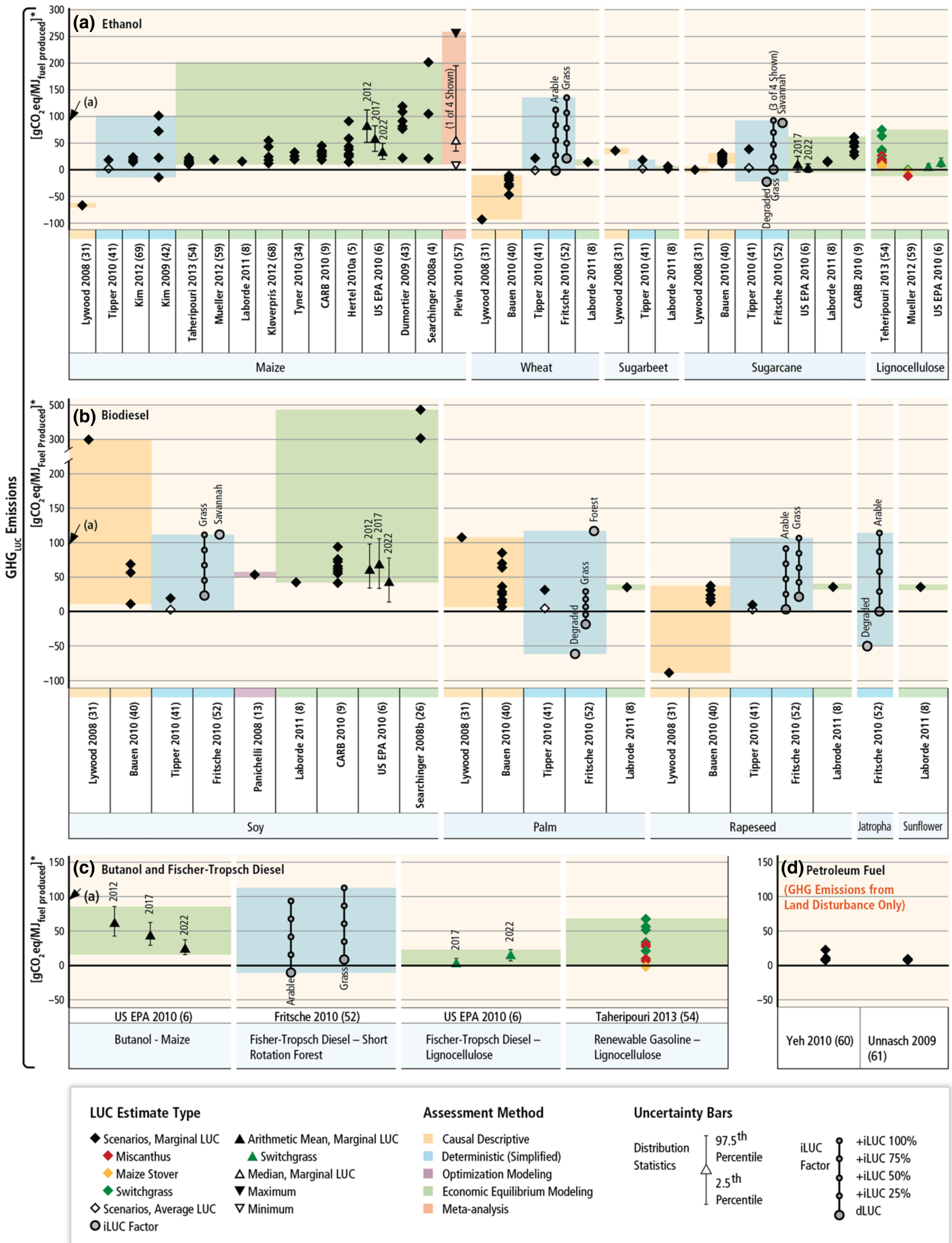
Additional 'site-specific' land-use considerations such as changes in soil organic carbon stocks ('ΔSOC'), changes in surface albedo ('Δalbedo'), and the skewed time distribution of terrestrial biogenic CO_2 fluxes can either reduce or compound land-use impacts and are presented to exemplify that, for some bioenergy systems, these impacts can be greater in magnitude than life-cycle impacts from feedstock cultivation and bioenergy product conversion. 'Site-specific' land-use considerations are geographically explicit and highly sensitive to background climate conditions, soil properties, biomass yields, and land management regimes. The figure reveals that studies find very different values depending on the boundaries of analysis chosen, site-specific effects and management methods. Site-specific characteristics, perspectives on spatial and time scale as well as initial conditions, will generally affect the results together with the choice of climate metrics applied.

Key point 5: Fuels from sugarcane, perennial grasses, crop residues and waste cooking oil and many forest products have lower attributional life-cycle emissions than other fuels, depending on N_2O emissions, fuel used in conversion process, forest carbon dynamics, and other site-specific factors and counterfactual dynamics (land-use change emissions can still be substantial, see Fig. 5).

Another important result is that albedo effects and site-specific CO_2 fluxes are highly variable for different forest systems and environmental conditions and determine the total climate forcing of bioenergy from forestry.

Direct land-use change

Direct land-use change (LUC) occurs when bioenergy crops displace other crops, pastures or forests, while ILUC results from bioenergy deployment triggering the conversion to cropland or pasture of lands, somewhere on the globe, to replace a fraction of the displaced crops (Delucchi, 2010; Hertel *et al.*, 2010; Searchinger *et al.*, 2008). Direct LUC to establish biomass cropping systems can increase net GHG emissions, for example if carbon rich ecosystems such as wetlands, forests or natural grasslands are brought into cultivation (Chum *et al.*, 2011; Gibbs *et al.*, 2008; UNEP, 2009). Biospheric C losses associated with LUC from some bioenergy schemes can be, in some cases, more than hundred times larger than the annual GHG savings from the assumed fossil fuel replacement (Chum *et al.*, 2011; Gibbs *et al.*, 2008). Impacts have been shown to be significantly reduced when a dynamic baseline includes future trends in global agricultural land use (Kløverpris & Mueller, 2013; this study accounts for 100 years, not for 30 years as e.g., in Searchinger *et al.*, 2008). Albeit at lower magnitude, beneficial direct LUC effects can also be observed, for example when some perennial grasses or woody plants replace annual crops grown with high fertilizer input, or where such plants are produced on lands with carbon-poor soils (Harper *et al.*, 2010;



GHG LUC Emissions
[gCO2eq/MJ fuel produced]*
(a) Ethanol
(a)
Lywood 2008 (31)
Tipper 2010 (41)
Kim 2012 (69)
Kim 2009 (42)
Taheripouri 2013 (54)
Mueller 2012 (59)
Laborde 2011 (8)
Kløverpris 2012 (68)
Tyner 2010 (34)
CARB 2010 (9)
Hertel 2010a (5)
US EPA 2010 (6)
Dumortier 2009 (43)
Searchinger 2008a (4)
Plevin 2010 (57)
(1 of 4 Shown)
2012
2017
2022
Maize
Lywood 2008 (31)
Bauen 2010 (40)
Tipper 2010 (41)
Fritsche 2010 (52)
Laborde 2011 (8)
Arable
Grass
Wheat
Lywood 2008 (31)
Tipper 2010 (41)
Laborde 2011 (8)
Sugarbeet
Lywood 2008 (31)
Bauen 2010 (40)
Tipper 2010 (41)
Fritsche 2010 (52)
US EPA 2010 (6)
Laborde 2011 (8)
CARB 2010 (9)
(3 of 4 Shown)
Savannah
Degraded
Grass
2017
2022
Sugarcane
Taheripouri 2013 (54)
Mueller 2012 (59)
US EPA 2010 (6)
Lignocellulose
(b) Biodiesel
[gCO2eq/MJ Fuel Produced]*
(a)
Lywood 2008 (31)
Bauen 2010 (40)
Tipper 2010 (41)
Fritsche 2010 (52)
Panichelli 2008 (13)
Laborde 2011 (8)
CARB 2010 (9)
US EPA 2010 (6)
Searchinger 2008b (26)
Grass
Savannah
2012
2017
2022
Soy
Lywood 2008 (31)
Bauen 2010 (40)
Tipper 2010 (41)
Fritsche 2010 (52)
Labrode 2011 (8)
Forest
Grass
Degraded
Palm
Lywood 2008 (31)
Bauen 2010 (40)
Tipper 2010 (41)
Fritsche 2010 (52)
Labrode 2011 (8)
Arable
Grass
Rapeseed
Fritsche 2010 (52)
Arable
Degraded
Jatropha
Laborde 2011 (8)
Sunflower
(c) Butanol and Fischer-Tropsch Diesel
[gCO2eq/MJ fuel produced]*
(a)
2012
2017
2022
US EPA 2010 (6)
Butanol - Maize
Arable
Grass
Fritsche 2010 (52)
Fisher-Tropsch Diesel – Short Rotation Forest
2017
2022
US EPA 2010 (6)
Fischer-Tropsch Diesel – Lignocellulose
Taheripouri 2013 (54)
Renewable Gasoline – Lignocellulose
(d) Petroleum Fuel
(GHG Emissions from Land Disturbance Only)
Yeh 2010 (60)
Unnasch 2009 (61)
LUC Estimate Type
Scenarios, Marginal LUC
Miscanthus
Maize Stover
Switchgrass
Scenarios, Average LUC
iLUC Factor
Arithmetic Mean, Marginal LUC
Switchgrass
Median, Marginal LUC
Maximum
Minimum
Assessment Method
Causal Descriptive
Deterministic (Simplified)
Optimization Modeling
Economic Equilibrium Modeling
Meta-analysis
Uncertainty Bars
Distribution Statistics
97.5th Percentile
2.5th Percentile
iLUC Factor
+iLUC 100%
+iLUC 75%
+iLUC 50%
+iLUC 25%
dLUC

Sochacki *et al.*, 2012; Sterner & Fritsche, 2011; Tilman *et al.*, 2006) (Brandão *et al.*, 2011), including degraded lands (Wicke *et al.*, 2008, 2011a) and marginal croplands where cultivation of annual food/feed crops is not economically viable and where planting of bioenergy feedstock is less likely to cause ILUC (Gelfand *et al.*, 2013).

A range of agro-ecological options to improve agricultural practices such as no/low tillage conservation, and agroforestry have potential to increase yields (e.g., in sub-Saharan Africa), while also providing a range of co-benefits such as increased soil organic matter. Such options require a much lower level of investment and inputs and are thus more readily applicable in developing countries, while also holding a low risk of increased GHG emissions (Keating *et al.*, 2013).

Bioenergy from forests

In large managed forest estates, management activities in one stand are coordinated with activities elsewhere in the landscape with the purpose to provide a steady flow of harvested wood. While carbon stock decreases in stands that are harvested, carbon stock increases in other stands resulting in landscape-level carbon stock that fluctuates around a trend line that can be increasing or decreasing, or remain roughly stable (Berndes *et al.*, 2013; Hudiburg *et al.*, 2011; Lundmark *et al.*, 2014). Changes in the management of forests to provide biomass for energy can result in both losses and gains in forest carbon stocks, which are determined by the dynamics of management operations and natural biotic and abiotic forces (Cherubini *et al.*, 2012; Hudiburg *et al.*, 2011; Lundmark *et al.*, 2014). Bioenergy implementation may also affect other forest based industry sectors (e.g., building sector, pulp and paper, panel industry), which can provide favorable climate mitigation benefits (Lippke *et al.*, 2011; Pingoud *et al.*, 2012; Ximenes *et al.*, 2012).

Carbon and GHG balances also depends on policy formulation, e.g., restricted feedstock eligibility on bioenergy markets can reduce the GHG reduction benefits (Daigneault *et al.*, 2012; Latta *et al.*, 2013).

The design of the assessment framework has a strong influence on the calculated carbon balance (Berndes *et al.*, 2013; Lamers & Junginger, 2013). Carbon accounting at the stand level that start the accounting when biomass is harvested for bioenergy naturally finds upfront carbon losses that is found to delay net GHG savings up to several decades (carbon debt, e.g., Pingoud *et al.*, 2012). Assessments over larger landscapes report both forest carbon gains (Lundmark *et al.*, 2014) and losses delaying the GHG reduction benefit (Latta *et al.*, 2013; McKechnie *et al.*, 2011), as well as reductions in forest sink strength (foregone carbon sequestration) reducing or even outweighing for some period of time the GHG emissions savings from displacing fossil fuels (Haberl *et al.*, 2012; Holtsmark, 2012; Hudiburg *et al.*, 2011).

Intensive forest management activities of the early- to mid-20th century as well as other factors such as recovery from past overuse, have led to strong forest C-sinks in many OECD regions (Erb *et al.*, 2013; Loudermilk *et al.*, 2013; Nabuurs *et al.*, 2013; Pan *et al.*, 2011). However, the sink capacity decreases as forests approach maturity (Körner, 2006; Nabuurs *et al.*, 2013; Smith, 2005). Climate change mitigation strategies needs to recognize the possible carbon sink/source function of growing forests and the full range of forest products including their fossil carbon displacement capacity and the timing of emissions when carbon is stored in forest products over varying time scales (Lippke *et al.*, 2011). Active management can in some forest landscapes promote further sequestration and provide a steady output of biomass for bioenergy and other forest products, resulting in continuous fossil substitution benefits also when the sink strength of the forest eventually saturates (Canadell & Raupach, 2008; Ciais *et al.*, 2008; Lundmark *et al.*, 2014; Nabuurs *et al.*, 2007, 2013).

The anticipation of positive market development for bioenergy and other forest products may promote changes in forest management practices and net growth in forest area, contributing to increased carbon stocks, but may cause ILUC (Sedjo & Tian, 2012) (Dale *et al.*, 2013; Eisenbies *et al.*, 2009). Conservation of high

Fig. 5 Estimates of GHG_{LUC} emissions – GHG emissions from biofuel production-induced LUC (as g CO_2eq $MJ_{fuel\ produced}{}^{-1}$) over a 30 year time horizon organized by fuel(s), feedstock, and study. Assessment methods, LUC estimate types and uncertainty metrics are portrayed to demonstrate the diversity in approaches and differences in results within and across any given category. Points labeled 'a' on the *y* axis represent a commonly used estimate of life-cycle GHG emissions associated with the direct supply chain of petroleum gasoline (frame a) and diesel (frame b) and Fischer-Tropsch diesel (frame c). For comparison the GHG emissions from land disturbances of petroleum fuels are also given (frame d). These emissions are not directly comparable to GHG_{LUC} because the emission sources considered are different, but are potentially of interest for scaling comparison. Based on (Warner *et al.*, 2013). Please note: These estimates of global LUC are highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the modeling. All entries are not equally valid nor do they attempt to measure the same metric despite the use of similar naming conventions (e.g., ILUC). In addition, many different approaches to estimating GHG_{LUC} have been used. Therefore, each paper has its own interpretation and any comparisons should be made only after careful consideration. *CO_2eq includes studies both with and without CH_4 and N_2O accounting.

carbon-stock densities in old forests that are not at high risk of disturbance may be preferable to intensive management for wood output, while harvest of other mature forests that are at high risk of disturbance and have low productivity may be the best option, although involving an initial period (decades) of net losses in forest carbon (Nabuurs *et al.*, 2013).

In short, biomass that would otherwise be burned without energy recovery, rapidly decomposing residues and organic wastes can produce close to immediate GHG savings when used for bioenergy (Zanchi *et al.*, 2011), similarly to increasing the biomass outtake from forests affected by high mortality rates (Lamers *et al.*, 2013). When slowly decomposing residues are used and when changes in forest management to provide biomass for energy causes reductions in forest carbon stocks or carbon sink strength, the GHG mitigation benefits are delayed, sometimes many decades (Repo *et al.*, 2011). Conversely, when management changes in response to bioenergy demand so as to enhance the sink strength in the forest landscape, this improves the GHG mitigation benefit.

Indirect land-use change

Indirect land-use change is difficult to ascertain because the magnitude of these effects must be modeled (Nassar *et al.*, 2011) raising important questions about model validity and uncertainty (Gawel & Ludwig, 2011; Khanna *et al.*, 2011; Liska & Perrin, 2009; Plevin *et al.*, 2010; Wicke *et al.*, 2012) and about policy implications (DeCicco, 2013; Finkbeiner, 2013; Plevin *et al.*, 2013). Most available model-based studies have consistently found positive and, in some cases, high emissions from LUC and ILUC, mostly of first-generation biofuels, albeit with high variability and uncertainty in results (Warner *et al.*, 2013; see also Chen & Khanna, 2012; Creutzig & Kammen, 2010; Dumortier *et al.*, 2011; Havlík *et al.*, 2011; Hertel *et al.*, 2010; Taheripour *et al.*, 2011; Timilsina *et al.*, 2012) Causes of the large uncertainty include: incomplete knowledge of global economic dynamics (trade patterns, land-use productivity, diets, use of by-products, fuel prices and elasticities); selection of specific policies modeled; and the treatment of emissions over time (Khanna *et al.*, 2011; O'Hare *et al.*, 2009; Wicke *et al.*, 2012). In addition, LUC modeling philosophies, model structures, and features (e.g., dynamic vs. static models, partial vs. general equilibrium) differ among studies. Variations in estimated GHG emissions from biofuel-induced LUC are also driven by differences in scenarios assessed, varying assumptions, inconsistent definitions across models (e.g., LUC, land type), specific selection of reference scenarios against which (marginal) LUC is quantified, and disparities in data availability and quality. The general lack of thorough sensitivity and uncertainty analysis hampers the evaluation of plausible ranges of estimates of GHG emissions from LUC.

Key point 6: Land-use change associated with bioenergy implementation can have a strong influence on the climate benefit. Indirect land-use effects and other consequential changes are difficult to model and uncertain, but are nonetheless relevant for policy analysis.

Wicke *et al.* (2012) identified the need to incorporate the impacts of ILUC prevention or mitigation strategies in future modeling efforts, including the impact of zoning and protection of carbon stocks, selective sourcing from low risk areas, policies and investments to improve agricultural productivity, double cropping, agroforestry schemes and the (improved) use of degraded and marginal lands. ILUC is mostly assumed to be avoided in the modeled mitigation pathways of global stabilization scenarios. The relatively limited number of fuels covered in the literature precludes a complete set of direct comparisons across alternative and conventional fuels sought by regulatory bodies and researchers.

GHG emissions from LUC can be reduced, for instance through production of bioenergy coproducts that displace additional feedstock requirements thus decreasing the net area needed (e.g., for corn, Wang *et al.*, 2011; for wheat, Berndes *et al.*, 2011). Examples have been presented where the land savings effect of coproducts use as livestock feed more than outweigh the land claim of the bioenergy feedstock (Lywood *et al.*, 2009; Weightman *et al.*, 2011). Appropriate management of livestock and agriculture can lead to improved resource efficiency, lower GHG emissions and lower land use while releasing land for bioenergy or food production as demonstrated for Europe (De Wit *et al.*, 2013) and Mozambique (Van der Hilst *et al.*, 2012a).

Producing biofuels from wastes and sustainably harvested residues, and replacing first-generation biofuel feedstocks with lignocellulosic plants (e.g., grasses) may mitigate ILUC, especially if incentives exist for planting lignocellulosic plants on lands where cultivation of conventional food/feed crops is difficult (Davis *et al.*, 2012; Scown *et al.*, 2012). While ILUC quantifications remain uncertain, lower agricultural yields, land-intensive diets, and livestock feeding efficiencies, stronger climate impacts and higher energy crop production levels can result in higher LUC-related GHG emissions. But ILUC impacts can also be reduced (De Wit *et al.*, 2011, 2013; Fischer *et al.*, 2010; Rose *et al.*, 2013; Van Dam *et al.*, 2009a,b; Van der Hilst *et al.*, 2012a; Wicke *et al.*, 2009).

Key point 7: LUC impacts can be mitigated through: reduced land demand for food, fiber and bioenergy (e.g., diets, yields, efficient use of biomass, e.g., utilizing waste and residues); synergies between different land-use systems using adapted feedstocks (e.g., use hardy plants to cultivate degraded lands not suitable for conventional food crops); and governance systems and development models to protect ecosystems and promote sustainable land-use practices where land is converted to make place for biomass production.

Indirect effects are not restricted to indirect GHG effects of production of biomass in agricultural systems, but could also be relevant to bioenergy from wood sources. In addition, indirect effects could also apply to biodiversity threats, environmental degradation, and external social costs, which are not considered here (see sections Bioenergy and sustainable development and Trade-offs and synergies with land, water, food and biodiversity below). As with any other renewable fuel, bioenergy can replace or complement fossil fuel. When a global cap on CO_2 emissions is absent, the amount of displaced fossil fuels is highly uncertain, and depends on the relative price elasticities of supply and demand for fuels (Chen & Khanna, 2012; Drabik & De Gorter, 2011; Hochman *et al.*, 2010; Rajagopal *et al.*, 2011; Thompson *et al.*, 2011b).

Future potential deployment in climate mitigation scenarios

Climate mitigation scenarios are commonly explored in so-called Integrated Assessment Models. These models specify sets of technologies and explore cost-efficient mitigation options under various assumptions, for example with and without BECCS being available. These models consider the global economy in equilibrium and focus on timescales of up to 100 years. These models mostly report mitigation options assuming strong global governance, e.g., a price on GHG emissions. In the following, we report the results of these models.

In the IPCC SRREN scenarios, bioenergy is projected to contribute 80–190 EJ yr^{-1} to global primary energy supply by 2050 for 50% of the scenarios in the two climate mitigation levels modeled. The ranges were 20–265EJ yr^{-1} for the less stringent scenarios and 25–300 EJ for the tight climate mitigation scenarios (<440 ppm). Many of these scenarios coupled bioenergy with CCS. The GEA (2012) scenarios project 80–140 EJ by 2050, including extensive use of agricultural residues and second-generation bioenergy to try to reduce the adverse impacts on land use and food production, and the coprocessing of biomass with coal or natural gas with CCS to make low net GHG-emitting transport fuels and or electricity.

Traditional biomass demand is steady or declines in most scenarios from 34 EJ yr^{-1}. The transport sector increases nearly tenfold from 2008 to 18–20 EJ yr^{-1} while modern uses for heat, power, combinations, and industry increase by factors of 2–4 from 18 EJ in 2008 (Fischedick *et al.*, 2011). The 2010 IEA model projects a contribution of 12 EJ yr^{-1} (11%) by 2035 to the transport sector, including 60% of advanced biofuels for road and aviation. Bioenergy supplies 5% of global power generation in 2035, up from 1% in 2008. Modern heat and industry doubles their contributions from 2008 (IEA, 2010c). The future potential deployment level varies at the global and national level depending on the technological developments, land availability, financial viability and mitigation policies.

Transformation pathway studies suggest that modern bioenergy could play a significant role within the energy system, providing 5–95 EJ yr^{-1} in 2030, 10–245 EJ yr^{-1} in 2050 and 105–325 EJ yr^{-1} in 2100 under full implementation scenarios, with immediate, global, and comprehensive incentives for land-related mitigation options. The scenarios project increasing deployment of bioenergy with tighter climate change targets, both in a given year as well as earlier in time. Models project increased dependence on, as well as increased deployment of, modern bioenergy, with some models projecting 35% of total primary energy from bioenergy in 2050, and as much as 50% of total primary energy from modern bioenergy in 2100. Bioenergy's share of regional total electricity and liquid fuels could be significant – up to 35% of global regional electricity from biopower by 2050, and up to 70% of global regional liquid fuels from biofuels by 2050. However, the cost-effective allocation of bioenergy within the energy system varies across models.

The high biomass deployment in scenarios from integrated assessment models is not uncontested. In particular, another class of sectoral studies, focusing on biophysical constraints, model assumptions (e.g., estimated increase in crop yields over large areas), and current observations, suggest to focus on the lower half of the ranges reported above (Campbell *et al.*, 2008; Field *et al.*, 2008; Haberl *et al.*, 2013c; Johnston *et al.*, 2009, 2011).

BECCS features prominently in many transformation scenarios. BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy. Whether BECCS is essential for mitigation, or even sufficient, is unclear. The likelihood of BECCS deployment is difficult to evaluate and depends on safety confirmations, affordability and public acceptance (see section

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Bioenergy technologies for details). BECCS may also affect the cost-effective emissions trajectory (Blanford *et al*., 2013; Rose *et al*., 2013).

Some integrated models are cost-effectively trading-off lower land carbon stocks and increased land N_2O emissions for the long-run mitigation benefits of bioenergy (A. Popp *et al*., 2013; Rose *et al*., 2013). These models suggest that in an optimal world bioenergy could contribute effectively to climate change mitigation despite land conversion and intensification emissions. In these models, constraining bioenergy has a cost. For instance, limiting global bioenergy availability to 100 EJ yr^{-1} tripled marginal abatement costs and doubled consumption losses associated with transformation pathways (Rose *et al*., 2013).

Key point 8: Overall outcomes may depend strongly on governance of land use, increased yields, and deployment of best practices in agricultural, forestry and biomass production.

With increasing scarcity of productive land, the growing demand for food and bioenergy may incur substantial LUC causing high GHG emissions and/or increased agricultural intensification and higher N_2O emissions (Delucchi, 2010) unless wise integration of bioenergy into agriculture and forestry landscapes occurs. Integrated assessment models differ in their assumptions on availability of land resources for dedicated bioenergy crops. Either bioenergy crops will be allocated based on suitability of soil and climatic conditions and the competition with land needed for the production of other agricultural goods or bioenergy crops can only to be grown on land other than that required for food production. In general, avoiding deforestation restricts the availability for agricultural expansion. In some models nature conservation areas are not available for cropland expansion. Other models emphasize afforestation as an alternative to bioenergy as land-based carbon sequestration strategy. Different choices of bioenergy feedstocks (1st vs. 2nd generation but also woody vs. herbaceous cellulosic), land-use restrictions and current, as well as future management (such as irrigation vs. rainfed) for bioenergy production significantly affect simulated bioenergy crop yields. Agricultural yields in all models are assumed to change over time. Yield increases due to technological change are either considered mostly exogenously or treated endogenously. In some models food demand reacts to food prices and lower food demand is observed in mitigation scenarios. In other models, food demand is prescribed exogenously and therefore does react on higher food prices. As a result of ongoing population growth, rising per capita caloric intake and changing dietary preferences, such as an increased consumption of meat and dairy products, demand for agricultural products in the future is anticipated to increase significantly (Popp *et al*., 2013). Many models suggest relatively high deployment of bioenergy, as ambitious mitigation goals rely on making use of all available renewables. In particular, bioenergy is seen as more versatile, while solar and wind energy cannot as easily produce base load power or provide high-density fuels for transportation. If bioenergy, and especially BECCS, is not available, large-scale afforestation is seen as a necessary alternative land carbon sequestration strategy.

Consideration of LUC emissions in integrated assessment models show that valuing or protecting global terrestrial carbon stocks reduces the potential LUC-related GHG emissions of energy crop deployment, and could lower the cost of achieving climate change objectives, but could exacerbate increases in agricultural commodity prices (Popp *et al*., 2011; Reilly *et al*., 2012). It is important to note that integrated models are mostly investigating optimal realization pathways, assuming global prices on carbon (including the terrestrial land carbon stock); if such conditions cannot be realized, certain types of bioenergy could lead to additional GHG emissions. More generally, if the terrestrial land carbon stock remains unprotected, large GHG emissions from bioenergy related land-use change alone are possible (Calvin *et al*., 2013; Creutzig *et al*., 2012a; Melillo *et al*., 2009; Wise *et al*., 2009).

In summary, integrated model scenarios project between 10 and 245 EJ yr^{-1} modern bioenergy deployment in 2050. Good governance and favorable conditions for bioenergy development may result in higher deployment in bioenergy scenarios while sustainability and livelihood concerns might constrain the deployment of bioenergy scenarios to lower deployment values (see next section).

Bioenergy and sustainable development

The nature and extent of the impacts of deploying bioenergy depend on the specific system, the development context and on the size of the intervention. The effects on livelihoods have not yet been systematically evaluated in integrated assessments (Creutzig *et al*., 2012b), even though human geography studies have shown that bioenergy deployment can have strong distributional impacts (Davis *et al*., 2013; Muys *et al*., 2014). The total effects on livelihoods will be mediated by global market dynamics, policy regulations and incentives, the production model and deployment scale, and place-specific factors such as labor and financial capabilities, governance, including land tenure security, among others (Creutzig *et al*., 2013).

Bioenergy projects can be economically beneficial, e.g., by raising and diversifying farm incomes and increasing rural employment through the production of biofuels for domestic (Gohin, 2008) or export (Arndt *et al.*, 2011b,c) markets (Wicke *et al.*, 2009).

Box 1

Some reported examples of cobenefits from biofuel production

Brazilian sugar cane ethanol production provides six times more jobs than the Brazilian petroleum sector and spreads income benefits across numerous municipalities (De Moraes *et al.*, 2010). Worker income is higher than in nearly all other agricultural sectors (De Moraes *et al.*, 2010; Satolo & Bacchi, 2013) and several sustainability standards have been adopted (Viana & Perez, 2013). Broader strategic planning, understanding of cumulative impacts, and credible and collaborative decision-making processes can help to enhance biodiversity and reverse ecological fragmentation, address direct and indirect land-use change, improve the quality and durability of livelihoods, and other sustainability issues (Duarte *et al.*, 2013).

Cobenefits of palm oil production have been reported in the major producer countries, Malaysia and Indonesia (Lam *et al.*, 2009; Sumathi *et al.*, 2008) as well as from new producer countries (Garcia-Ulloa *et al.*, 2012). Palm oil production results in employment creation as well as in increments of state and individual income (Lam *et al.*, 2009; Sayer *et al.*, 2012; Sumathi *et al.*, 2008; Tan *et al.*, 2009; Von Geibler, 2013). When combined with agroforestry palm oil plantations can increase food production locally and have a positive impact on biodiversity (Garcia-Ulloa *et al.*, 2012; Lam *et al.*, 2009) and when palm oil plantations are installed on degraded land further cobenefits on biodiversity and carbon enhancement may be realized (Garcia-Ulloa *et al.*, 2012; Sayer *et al.*, 2012; Sumathi *et al.*, 2008). Further, due to its high productivity palm oil plantations can produce the same bioenergy input using less land than other bioenergy crops (Sumathi *et al.*, 2008; Tan *et al.*, 2009). Certification in palm oil production can become a means for increasing sustainable production of biofuels (Tan *et al.*, 2009; Von Geibler, 2013).

Similarly, cobenefits from the production of Jatropha as a biofuel crop in developing countries have been reported, mainly when Jatropha is planted on degraded land. These include increases in individuals income (Arndt *et al.*, 2012; Garg *et al.*, 2011a,b), improvement in energy security at the local level (Muys *et al.*, 2014; Von Maltitz & Setzkorn, 2013), and reducing soil erosion (Garg *et al.*, 2011a,b).

The establishment of large-scale biofuels feedstock production, however, can also cause smallholders, tenants and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, and populations who are closer to for GHG emission reduction activities enjoy the benefits of this production (Van der Horst & Vermeylen, 2011). This is particularly relevant where large areas of land are still unregistered or are being claimed and under dispute by stakeholders (Dauvergne & Neville, 2010). In some cases increasing demand for first-generation bioenergy is partly driving the expansion of crops like soy and oil palm, which in turn contribute to promote large-scale agribusinesses at the expense of family and community-based agriculture (Wilkinson & Herrera, 2010). Biofuels deployment can also translate into reductions of time invested in on-farm subsistence and community-based activities, thus translating into lower productivity rates of subsistence crops and an increase in intracommunity conflicts as a result of the uneven share of collective responsibilities (Mingorría *et al.*, 2010, 2014).

Bioenergy deployment seems to be more beneficial when it is not an additional land-use activity expanding over the landscape, but rather integrates into existing land uses and influences the way farmers and forest owners use their land. Various studies indicate the ecosystem services and values that perennial crops have in restoring degraded lands, via agroforestry systems, controlling erosion and even in regional climate effects such as improved water retention and precipitation (Faaij, 2006; Van der Hilst *et al.*, 2012a; Wicke *et al.*, 2011b). Examples include adjustments in agriculture practices where farmers, for instance, change their manure treatment to produce biogas, reduce methane losses and reduce N losses. Changes in management practice may swing the net GHG balance of options and also have clear sustainable development implications (Davis *et al.*, 2012).

Small-scale bioenergy options can provide cost-effective alternatives for mitigating climate change, at the same time helping advance sustainable development priorities, particularly in rural areas of developing countries (see Box 1). The IEA (2011) estimates that 2.7 billion people worldwide depend on traditional biomass for cooking, while 84% of them belonged to rural communities. Use of low quality fuels and inefficient cooking and heating devices leads to pollution resulting in nearly 4 million premature deaths every year, and a range of chronic illnesses and other health problems (Lim *et al.*, 2012). Modern small-scale bioenergy systems reduce CO_2 emissions from unsustainable biomass harvesting and short-lived climate pollutants, e.g., black carbon, from cleaner combustion (Chung *et al.*, 2012;

FAO, 2010). As noted previously, scaling up clean cookstove initiatives could not only save 2 million lives a year, but also significantly reduce GHG emissions. Efficient biomass cookstoves and biogas stoves at the same time provide multiple benefits: reduce pressure on forests and biodiversity, reduce exposure to smoke related health hazards, reduce drudgery for women in collecting fuelwood and save money if purchasing fuels (Martin *et al*., 2011). Benefits from the dissemination of improved cookstoves outweigh their costs by 7-fold, when their health, economic, and environmental benefits are accounted for (Garcia-Frapolli *et al*., 2010).

Table 1 presents a summary of potential impacts of bioenergy options on social, institutional, environmental, economic and technological conditions. The relationship between bioenergy and these conditions is complex and there could be negative or positive implications, depending on the type of bioenergy option, the scale of the production system and the local context, allowing intrinsic trade-offs (Edenhofer *et al*., 2013). While biofuels can allow the reduction of fossil fuel use and of greenhouse gas emissions, they often shift environmental burdens toward land use-related impacts (i.e., eutrophication, acidification, water depletion, ecotoxicity) (EMPA, 2012; Smith & Torn, 2013; Tavoni & Socolow, 2013). Cobenefits and adverse side effects do not necessarily overlap, neither geographically nor socially (Dauvergne & Neville, 2010; Van der Horst & Vermeylen, 2011; Wilkinson & Herrera, 2010). The main potential cobenefits are related to access to energy and impacts on the economy and wellbeing, jobs creation and improvement of local resilience (Creutzig *et al*., 2013; Walter *et al*., 2011). Main risks of crop-based bioenergy for sustainable development and livelihoods include competition on arable land (Haberl *et al*., 2013a) and consequential impact on food security, tenure arrangements, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water and soil or increment in vulnerability to climate change, and unequal distribution of benefits (German *et al*., 2011; Hall *et al*., 2009; Sala *et al*., 2000; SREX, 2012; Thompson *et al*., 2011a,b).
Key point 9: The management of natural resources to provide needs for human society while recognizing environmental balance is the challenges facing society. Good governance is an essential component of a sustainable energy system.

Careful policies for implementation focused on land-use zoning approaches (including nature conservation and biodiversity protection), multifunctional land use, integration of food and energy production, avoidance of detrimental livelihood impacts e.g., on livestock grazing and subsistence farming, and consideration of equity issues and sound management of impacts on water systems are crucial for sustainable solutions. Integrated studies that compare impacts of bioenergy production between different crops and land management strategies show that the overall impact (both ecological and socio-economic) depends strongly on the governance of land use and design of the bioenergy system (see Van der Hilst *et al*., 2012b in the European context and Van Dam *et al*., 2009a,b for different crops and scenarios in Argentina). Van Eijck *et al.* (2012) show similar differences in impacts between the production and use of Jatropha based on smallholder production vs. plantation models. This implies that governance and planning have a strong impact on the ultimate result and impact of large-scale bioenergy deployment. Legislation and regulation of bioenergy as well as voluntary certification schemes are required to guide bioenergy production system deployment so that the resources and feedstocks be put to best use, and that (positive and negative) socio-economic and environmental issues are considered and addressed when needed (Batidzirai *et al*., 2012; Baum *et al*., 2012; Berndes *et al*., 2008, 2004; Börjesson & Berndes, 2006; Busch, 2012; Dimitriou *et al*., 2009, 2011; Dornburg *et al*., 2010; Garg *et al*., 2011a,b; Gopalakrishnan *et al*., 2012, 2011a,b; Gopalakrishnan *et al*., 2009; Parish *et al*., 2012; Sparovek *et al*., 2007). But the global potentials of such systems are difficult to determine (Berndes & Börjesson, 2007; Dale & Kline, 2013). Similarly, existing and emerging guiding principles and governance systems influence biomass resources availability (Stupak *et al*., 2011). In this regard, certification approaches can be useful, but they should be accompanied by effective territorial policy frameworks (Hunsberger *et al*., 2013). There are different options, from voluntary to legal and global agreements, to improve governance of biomass markets and land use that still require much further attention (Verdonk *et al*., 2007).

Trade-offs and synergies with land, water, food and biodiversity

This section summarizes results from integrated models (models that have a global aggregate view, but cannot disaggregate place-specific effects in biodiversity and livelihoods discussed above) on land, water, food and biodiversity. In these models, at any level of future bioenergy supply, land demand for bioenergy depends on (i) the share of bioenergy derived from wastes and residues (Rogner *et al*., 2012); (ii) the extent to which bioenergy production can be integrated with food or fiber production, which ideally results in synergies (Garg *et al*., 2011a,b; Sochacki *et al*., 2012) or at least mitigates land-use competition (Berndes *et al*., 2013); (iii) the

Table 1 Potential institutional, social, environmental, economic, and technological implications of bioenergy options at local to global scale

	Scale	
Institutional issues and Governance systems		
May contribute to energy independence (+), especially at the local level (reduce dependency on fossil fuels) (2, 20, 32, 39, 50)	+	Local to national
Can improve (+) or decrease (−) land tenure and use rights for local stakeholders (2, 17, 38, 50)	+/−	Local
Cross-sectoral coordination (+) or conflicts (−) between forestry, agriculture, energy and/or mining (2, 13, 26, 31, 59)	+/−	Local to national
Impacts on labor rights among the value chain (2, 6, 17)	+/−	Local to national
Promoting of participative mechanisms for small-scale producers (14, 15)	+	Local to national
Social		
Competition with food security including food availability (through reduced food production at the local level), food access (due to price volatility) use usage (as food crops can be diverted toward biofuel production) and consequently to food stability. Bioenergy derived from residues, wastes or by-products is an exception (1,2, 7, 9, 12, 18, 23)	−	Local to global
Integrated systems (including agroforestry) can improve food production at the local level creating a positive impact toward food security (51, 52, 53, 66, 70, 71, 72). Further, biomass production combined with improved agricultural management can avoid such competition and bring investment in agricultural production systems with overall improvements of management as a result (as observed in Brazil) (59, 62, 67, 68)	+	Local
Increasing (+) or decreasing (−) existing conflicts or social tension (9, 14, 19, 26)	+/−	Local to national
Impacts on traditional practices: using local knowledge in production and treatment of bioenergy crops (+) or discouraging local knowledge and practices (−) (2, 50)	+/−	Local
Displacement of small-scale farmers (14, 15, 19). Bioenergy alternatives can also empower local farmers by creating local income opportunities	+/−	Local
Promote capacity building and new skills (3, 15, 50)	+	Local
Gender impacts (2, 4, 14, 15, 27)	+/−	Local to national
Efficient biomass techniques for cooking (e.g., biomass cookstoves) can have positive impacts on health specially for women and children in developing countries (42, 43, 44)	+	Local to national
Environmental		
Biofuel plantations can promote deforestation and/or forest degradation, under weak or no regulation (1, 8, 22)	−	Local to global
When used on degraded lands, perennial crops offer large-scale potential to improve soil carbon and structure, abate erosion and salinity problems. Agroforestry schemes can have multiple benefits including increased overall biomass production, increase biodiversity and higher resilience to climate changes (58, 63, 64, 66, 71)	+	Local to global
Some large-scale bioenergy crops can have negative impacts on soil quality, water pollution and biodiversity. Similarly potential adverse side effects can be a consequence of increments in use of fertilizers for increasing productivity (7, 12, 26, 30). Experience with sugarcane plantations has shown that they can maintain soil structure (56) and application of pesticides can be substituted by the use of natural predators and parasitoids (68)	−/+	Local to transboundary
Can displace activities or other land uses (8, 26)	−	Local to global
Smart modernization and intensification can lead to lower environmental impacts and more efficient land use (73, 74)	+	Local to transboundary
Creating bioenergy plantations on degraded land can have positive impacts on soil and biodiversity (12)	+	Local to transboundary
There can be trade-offs between different land uses, reducing land availability for local stakeholders (45, 46, 47, 48, 49). Multicropping system provide bioenergy while better maintaining ecological diversity and reducing land use competition (57)	−/+	Local to national
Ethanol utilization leads to the phase-out of lead additives and MBTE and reduces sulfur, particulate matter and carbon monoxide emissions (55)	+	Local to global
Economic		
Increase in economic activity, income generation and income diversification (1, 2, 3, 12, 20, 21, 27, 54)	+	Local
Increase (+) or decrease (−) market opportunities (16, 27, 31)	+/−	Local to national
Contribute to the changes in prices of feedstock (2, 3, 5, 21)	+/−	Local to global

Table 1 (continued)

	Scale	
May promote concentration of income and/or increase poverty if sustainability criteria and strong governance is not in place (2, 16, 26)	−	Local to regional
Using waste and residues may create socio-economic benefits with little environmental risks (2, 41, 36)	+	Local to regional
Uncertainty about mid- and long term revenues (6, 30)	−	National
Employment creation (3, 14, 15)	+	Local to regional
Technological		
Can promote technology development and/or facilitate technology transfer (2, 27, 31)	+	Local to global
Increasing infrastructure coverage (+). However if access to infrastructure and/or technology is reduced to few social groups it can increase marginalization (−) (27, 28, 29)	+/−	Local
Bioenergy options for generating local power or to use residues may increase labor demand, creating new job opportunities. Participatory technology development also increases acceptance and appropriation (6, 8, 10, 37, 40)	+	Local
Technology might reduce labor demand (−). High dependent of tech. transfer and/or acceptance	−	Local

(1) (Finco & Doppler, 2010); (2) (Amigun *et al.*, 2011); (3) (Arndt *et al.*, 2012); (4) (Arndt *et al.*, 2011a); (5) (Arndt *et al.*, 2011a,b); (6) (Awudu & Zhang, 2012); (7) (Beringer *et al.*, 2011); (8) (Borzoni, 2011); (9) (Bringezu *et al.*, 2012); (10) (Cacciatore *et al.*, 2012); (11) (Cançado *et al.*, 2006); (12) (Danielsen *et al.*, 2009);(13) (Diaz-Chavez, 2011); (14) (Duvenage *et al.*, 2013); (15) (Ewing & Msangi, 2009); (16) (Gasparatos *et al.*, 2011); (17) (German & Schoneveld, 2012); (18) (Haberl *et al.*, 2011); (19) (Hall *et al.*, 2009); (20) (Hanff *et al.*, 2011); (21) (Huang *et al.*, 2012); (22) (Koh & Wilcove, 2008); (23) (Koizumi, 2013); (24) (Kyu *et al.*, 2010); (25) (Madlener *et al.*, 2006); (26) (Martinelli & Filoso, 2008); (27) (Mwakaje, 2012); (28) (Oberling *et al.*, 2012); (29) (Schut *et al.*, 2010); (30) (Selfa *et al.*, 2011); (31) (Steenblik, 2007); (32) (Stromberg & Gasparatos, 2012); (33) (Searchinger *et al.*, 2009); (34) (Searchinger *et al.*, 2008); (35) (Smith & Searchinger, 2012); (36) (Tilman *et al.*, 2009); (37) (Van de Velde *et al.*, 2009); (38) (Von Maltitz & Setzkorn, 2013); (39) (Wu & Lin, 2009); (40) (Zhang *et al.*, 2011); (41) (Fargione *et al.*, 2008); (42) (Jerneck & Olsson, 2013); (43) (Gurung & Oh, 2013); (44) (O'Shaughnessy *et al.*, 2013); (45) (German *et al.*, 2013); (46) (Cotula, 2012); (47) (Mwakaje, 2012); (48) (Scheidel & Sorman, 2012); (49) (Haberl *et al.*, 2013b); (50) (Muys *et al.*, 2014); (51) (Egeskog *et al.*, 2011); (52) (Diaz-Chavez, 2012); (53) (Ewing & Msangi, 2009); (54) (De Moraes *et al.*, 2010); (55) (Goldemberg, 2007); (56) (Walter *et al.*, 2008); (57) (Langeveld *et al.*, 2013); (58) (Van Dam *et al.*, 2009a,b); (59) (Van Dam *et al.*, 2010); (60) (Van Eijck *et al.*, 2012); (61) (van Eijck *et al.*, 2013, 2014); (62) (Martínez *et al.*, 2013); (63) (Van der Hilst *et al.*, 2010); (64) (Van der Hilst *et al.*, 2012a,b,c); (65) (Hoefnagels *et al.*, 2013); (66) (Immerzeel *et al.*, 2014); (67) (Lynd *et al.*, 2011); (68) (Smeets *et al.*, 2008); (69) (Smeets & Faaij, 2010); (70) (Wicke *et al.*, 2011a); (71) (Wicke *et al.*, 2013); (72) (Wiskerke *et al.*, 2010); (73) (De Wit *et al.*, 2011); (74) (De Wit *et al.*, 2013).

extent to which bioenergy can be grown on areas with little current or future production, taking into account growing land demand for food (Nijsen *et al.*, 2012); and (iv) the volume of dedicated energy crops and their yields (Batidzirai *et al.*, 2012; Haberl *et al.*, 2010; Smith *et al.*, 2012a). Energy crop yields per unit area may differ by factors of >10 depending on differences in natural fertility (soils, climate), energy crop plants, previous land use, management and technology (Beringer *et al.*, 2011; Erb, 2012; Johnston *et al.*, 2009; Lal, 2010; Pacca & Moreira, 2011; Smith *et al.*, 2012a). Assumptions on energy crop yields are one of the main reasons for the large differences in estimates of future area demand of energy crops (Popp *et al.*, 2013). Likewise, assumptions on yields, strategies and governance on future food/feed crops have large implications for assessments of the degree of land competition between biofuels and these land uses (Batidzirai *et al.*, 2012; De Wit *et al.*, 2013).

However, across models, there are very different potential landscape transformation visions in all regions. Overall, it is difficult to generalize on regional land cover effects of mitigation. Some models assume significant land conversion while other models do not. In idealized implementation scenarios, there is expansion of energy cropland and forest land in many regions, with some models exhibiting very strong forest land expansion and others very little by 2030. Land conversion is increased in the 450 ppm scenarios compared to the 550 ppm scenarios, but at a declining share, a result consistent with a declining land-related mitigation rate with policy stringency. The results of these integrated model studies need to be interpreted with caution, as not all GHG emissions and biogeophysical or socio-economic effects of bioenergy deployment are incorporated into these models, and as not all relevant technologies are represented (e.g., cascade utilization).

Large-scale bioenergy production from dedicated crops may affect water availability and quality, which are highly dependent on (i) type and quantity of local freshwater resources; (ii) necessary water quality; (iii) competition for multiple uses (agricultural, urban, industrial, power generation); and (iv) efficiency in all sector end-uses (Coelho *et al*., 2012; Gerbens-Leenes *et al*., 2009). In many regions, additional irrigation of energy crops could further intensify existing pressures on water resources (Popp *et al*., 2011). Studies indicate that an exclusion of severe water scarce areas for bioenergy production (mainly to be found in the Middle East, parts of Asia and western USA) would reduce global technical bioenergy potentials by 17% until 2050 (Van Vuuren *et al*., 2009). A model comparison study with five global economic models shows that the aggregate food price effect of large-scale lignocellulosic bioenergy deployment (i.e. 100 EJ globally by the year 2050) is significantly lower (+5% on average across models) than the potential price effects induced by climate impacts on crop yields [+25% on average across models (Lotze-Campen *et al*., 2013)]. Hence, ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, e.g., from forests, does not directly compete for agricultural land. Effective land-use planning and strict adherence to sustainability criteria need to be integrated to large-scale bioenergy projects to minimize competitions for water (for example, by excluding the establishment of biofuel projects in irrigated areas). If bioenergy is not managed properly, additional land demand and associated land use change may put pressures on biodiversity (Groom *et al*., 2008; Reilly *et al*., 2012; Popp *et al*., 2011; Wise *et al*., 2009). However, implementing appropriate management, such as establishing bioenergy crops in degraded areas represents an opportunity where bioenergy can be used to achieve positive environmental outcomes (Nijsen *et al*., 2012; Immerzeel *et al*., 2014).

Conclusion

The climate change mitigation value of bioenergy systems depends on several factors, some of which are challenging to quantify. We estimate the sustainable technical potential as up to 100 EJ: high agreement; 100–300 EJ: medium agreement; above 300 EJ: low agreement. Stabilization scenarios indicate that bioenergy may supply from 10 to 245 EJ yr^{-1} to global primary energy supply by 2050. Large-scale deployment (>200 EJ) could realize high GHG emissions savings if technological and governance preconditions are met, but such high deployment of land-intensive bioenergy feedstocks could also lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods otherwise. Cellulosic feedstocks, increased end-use efficiency, improved land carbon-stock management and residue use, and, when fully developed, carbon dioxide capture and storage from bioenergy appear as the most promising options, depending on development costs, implementation, learning, and risk management. The deployment of small-scale bioenergy systems such as biogas and efficient wood stoves for cooking, small-scale decentralized biomass combustion and gasification for rural electrification could not only reduce GHG emissions but also promote other dimensions of sustainable development.

One strand of literature highlights that bioenergy could contribute significantly to mitigating global GHG emissions via displacing fossil fuels, better management of natural resources, and possibly by deploying BECCS. Another strand of literature points to abundant risks in the large-scale development of bioenergy mainly from dedicated energy crops and particularly in reducing the land carbon stock, potentially resulting in net increases in GHG emissions.

The climate impacts of bioenergy systems are site and case specific, given the large dependence on local factors (especially for biogeophysical and biogeochemical aspects). For any bioenergy system to deliver net climate benefits with few negative environmental or socio-economic impacts, will require attention to a range of factors that influence land-use change related GHG emissions and biogeophysical perturbations; displacement of other land and water uses; other livelihood aspects such as employment, land access and social assets; and biodiversity. Other crucial factors influencing mitigation potential are biomass feedstock and production practices, the conversion technologies used, whether BECCS can be deployed economically and safely, and the magnitude of market-mediated effects such as ILUC and fossil fuel displacement. The estimated mitigation potential also depends on exactly how the accounting is performed (e.g., definition of baseline conditions and system boundaries).

We conclude that the high variability in pathways, uncertainties in technological development and ambiguity in political decision-making render forecasts on deployment levels and climate effects very difficult. Thus there is need for research and development to address many of these uncertainties. However, uncertainty about projections should not preclude pursuing clearly beneficial bioenergy options.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Attributional LCA.